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DYNAMICS OF REDOXIMORPHIC FEATURE FORMATION UNDER CONTROLLED PONDING IN A CREATED RIVERINE WETLAND

Michael J. Vepraskas[1], Jimmie L. Richardson[2], and John P. Tandarich[3]

[1]*North Carolina State University*
Soil Science Department
Box 7619
Raleigh, North Carolina, USA 27695-7619
E-mail: Michael_Vepraskas@NCSU.edu

[2]*U.S. Department of Agriculture, Natural Resources Conservation Service*
National Soil Survey Center
Federal Building
100 Centennial Mall, Room 152
Lincoln, Nebraska, USA 68508-5336

[3]*Dominican University*
Department of Biology
7900 W. Division St.
River Forest, Illinois, USA 60306

Abstract: Hydric soils are identified on-site using morphological features called ''field indicators''. It is not known how long it takes for these indicators to form, nor whether they occur in created wetlands inundated for approximately 5% of the growing season, which is the minimum duration needed to meet wetland hydrology requirements. This study evaluated formation of redoximorphic features and hydric soil field indicators under field conditions following controlled, short-term floods that produced ponding events. A flood plain was constructed along an artificial stream channel (100-m long) where flooding was controlled by dams at each end of the channel. Floodwaters inundated soils on the flood plain nine times over a 3-year period. Ponded water was kept on the soils for periods ranging from 4 to 44 days. During ponding events, Fe^{2+} concentrations were approximately 1 to 4 mg/L, which indicated that the soils were anaerobic and undergoing Fe reduction. Redox depletions formed in A horizons following a single 7-day ponding event. Abundance of depletions increased from 2% to an average of 15% after nine ponding events. Most depletions were approximately 1 cm in diameter and had Munsell hues of 2.5Y and 5Y, values of 4, and chromas of 2 or less. The depletions appeared to form in place by loss of both Fe and C. Hydric soil field indicators developed in all plots after nine ponding events over a 3-year period and included the depleted matrix, redox dark surface, and a variant of the depleted dark surface. All indicators formed by a reduction and/or oxidation of Fe.

Key Words: hydric soil indicators, oxidation-reduction, redoximorphic features, wetland delineation, wetland hydrology

INTRODUCTION

Jurisdictional wetlands are identified in the U.S. on the basis of three parameters: wetland hydrology, hydric soils, and hydrophytic vegetation (Environmental Laboratory 1987). Wetland hydrology is met if the soil is saturated to the surface for periods of at least 5% of the growing season with a frequency of at least 5 years out of 10. Hydric soils are defined as soils that formed under conditions of saturation, flooding, or ponding long enough during the growing season to develop anaerobic conditions in the upper part (National Technical Committee for Hydric Soils 1991, Federal Register 1994). These soils are identified on the basis of field indicators, which are well-defined layers of soil that span specific depths and have specific color patterns (USDA, NRCS 2002). If a soil meets a field indicator, then it is considered to be a hydric soil, but it may not be in a jurisdictional wetland unless the other two parameters are also met. The types of field indicators used to identify hydric soils vary between agricultural and non-agricultural lands, but the differences are not large (Environmental Laboratory 1987, USDA-NRCS 2002).

The wetland parameters used to identify jurisdictional wetlands were defined to be used separately, but clearly, they must be related to one another. Areas that have wetland hydrology and hydric soils must be saturated long enough to allow the soil chemical reactions that create anaerobic conditions needed for hydric soils and the formation of field indicators to occur. While federal regulations specify that saturation for 5% of the growing season is sufficient to meet the hydrology requirements for a jurisdictional wetland, this value may have little practical usefulness if hydric soils require periods of saturation lasting 12% or more of the growing season before the soils become anaerobic.

Relatively little work has been conducted on how long it takes hydric soil field indicators to form under field conditions. Field indicators formed by iron reduction and oxidation developed within five years after construction along the edge of a deep marsh in Illinois (Vepraskas et al. 1999). The most prevalent field indicator was the depleted matrix, which consisted of a layer of soil with 60% or more of its matrix having a low (<2) chroma color that was produced by iron reduction. Concentrations of Fe^{2+} in solution were between 1 and 6 mg/L in the zone where the depleted matrix had formed.

Redoximorphic features require a series of steps in order to form: (1) Fe or Mn need to be reduced; (2) these ions need to be solubilized, which usually occurs because the reduced forms are orders more soluble than the oxidized forms; (3) moved through the soil in solution; and (4) oxidized in zones of concentration (Vepraskas 1992). The removal of Fe and Mn creates zones within soil horizons that are usually gray in color and are called redox depletions. The concentration of Fe and Mn creates zones enriched in Fe and Mn that are usually red or yellow, occasionally black, that are called redox concentrations. Meek et al. (1968) found that Fe could be reduced within 3 d of inundation in plots to which chopped plant material had been added. Ferrous Fe concentrations in solution peaked at 5 mg/L when maximum air temperature averaged 26° C, but Fe^{2+} levels rose to nearly 30 mg/L when maximum air temperature was 40° C in similar soil plots. While Meek et al. (1968) did not examine the soil for morphological changes, redox depletions could have formed under the conditions of this experiment if the Fe^{2+} diffused through the soil matrix. Other studies have shown that Fe^{2+} can be produced in soils flooded for periods of three weeks or less but the amount of Fe produced depends on the soil, amount and oxide form of Fe present, amount of organic matter, and temperature among other factors (Ponnamperuma 1972 Macedo and Bryant 1989).

Individual redox concentrations have developed quickly in some experiments. Iron oxide coatings on roots have been created in pot experiments with rice (*Oryza sativa* L.) grown for 31 d in solutions having solution Fe^{2+} concentration between 1.3 and 26.8 mg/L (Bacha and Hosner 1977). Other experiments have created similar features after 7 d of flooding in the field, and the features increased in Fe concentration throughout the growing season (Chen et al. 1980). Chen et al. (1980) noted that the concentration of Fe in root coatings was related to the amount of total Fe in the soil; high clay content apparently acted as a minor inhibitor of coating formation, and the larger the amount of O_2 that a plant variety could translocate to the roots would increase root coatings.

The objective of this study was to determine if redoximorphic features and hydric soil field indicators can develop under short-term ponding events in a created riverine wetland. We tested the hypothesis that hydric soil field indicators could form in soils that were saturated for periods that were approximately 5% of the growing season.

MATERIALS AND METHODS

Experiments were conducted at the Des Plaines Wetlands Demonstration Project in Wadsworth, Illinois, USA about 56 km north of Chicago. The study site was located in Section 34, T 46 N, R 11 E; 42° 26′ N, 87° 56′ W. The soils studied were within a constructed landscape built to represent an artificial channel cut into a flood plain. The water table at base flow was below the depths studied. The flood plain was constructed in the C horizon of a Pella silt loam (fine-silty, mixed, superactive, mesic Typic Endoaquoll) that had been drained for agriculture. Parent materials were calcareous alluvium, lacustrine deposits, and glacial outwash overlain by loess (Kelsey and Hootman 1985).

The construction began by removing the A horizon (topsoil 25 to 50 cm thick) and stockpiling it. The channel and wetland basin (flood plain) were excavated as shown in Figure 1. The channel was approximately 100 m long and contained removable dams at both ends that allowed the experimenters to control the amount and timing of water entering and leaving the channel. Once the channel and flood plain had been graded to the target elevations, A-horizon material was reapplied in two strips perpendicular to the channel to a depth ranging between 8 and 40 cm. A-horizon material was thickest at the mid-plain position and thinned toward both the channel and back-plain. The site was hand-planted to sedges (*Carex aquatilis* L.) that were found in sedge meadow pockets that lay along riverbanks in this region.

Experimental plots were placed in transects located in the A horizon strips. Plots were labeled as shown

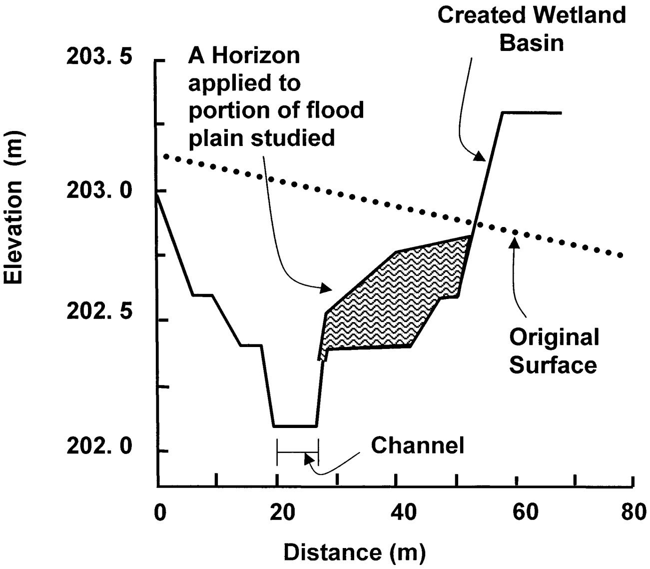

Figure 1. Cross-section of the flood plain wetland both before and after construction. The A horizon (topsoil 30 to 50 cm thick) material was removed from the original surface and stockpiled. The wetland basin was then graded to the specifications shown.

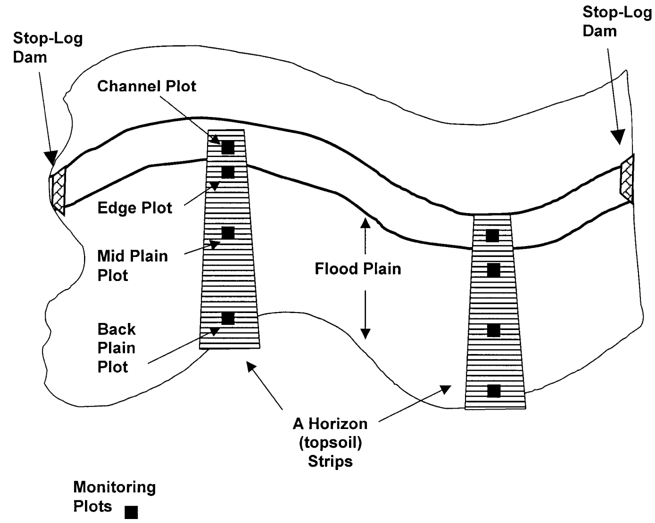

Figure 2. Locations of monitoring plots along transects in the flood plain wetland studied (not drawn to scale). The A horizon that was removed prior to construction was spread along two strips as shown. Each strip contained a replicate set of plots. Stop-log dams controlled water entry and exit. These dams were operated by hand by removing logs to allow water entry and then replacing logs to keep water from draining out. The source of water was the Des Plaines River, which flowed near the site. The channel shown was approximately 100 m long.

in Figure 2 to approximate various geomorphic positions expected from the channel to the upland. In each plot, piezometers were placed at depths of 30, 60, 100, and 200 cm, while a well was placed at a depth of 200 cm. Piezometers consisted of PVC pipe (3-cm diam, schedule 40) cut to lengths that allowed 60 cm of pipe to extend above ground. For piezometers, 30-mm-diameter holes were drilled in the bottom 8 cm of each pipe. Wells were constructed like piezometers with the exception that holes were drilled along the pipe with the uppermost hole being 15 cm below the soil surface after the well was installed. Holes in both the wells and piezometers were covered with a sleeve made of a porous geotextile that was secured to the tubes with tape.

Piezometers and wells were installed by augering a hole 10 cm in diameter to the appropriate depth. The piezometer was inserted and sand was tamped in and around the base of the piezometer to cover the holes and geotextile. The sand was covered by a bentonite cap that was estimated to be 5 cm thick. Soil was then used to fill the space around the piezometer between the surface and the bentonite cap. Water measurements were made by slipping a steel tape measure into the piezometer and listening for the sound made by the end of the tape striking the water surface. Depths to the water surface were measured relative to the soil surface.

Passive water samplers were constructed from 175 ml, square, plastic bottles with screw caps. Six 3-mm-diameter holes were drilled in each of the four sides of a bottle. The holes were covered by wrapping the bottle with fiberglass cloth (Bond Tite Products, no. 62255, POB 35908, Cleveland, OH 44135). The cloth was then covered by fiberglass window screen, which was held in place around the neck of the bottle with a plastic cable tie. Two straight hose-barb unions (5-mm I.D.) were installed in each cap and held in place with epoxy. One union had a piece of tygon tubing attached to it on the inside of the bottle, which reached to the bottom of the bottle. Tygon tubing was attached to each union on the outside of the cap and cut to lengths sufficient to extend 60 cm above the soil surface when the bottle was buried. The tygon tubing was held onto the unions with cable ties. Caps were firmly screwed onto each bottle before the bottle was brought to the field.

Water samplers were installed in each plot at depths of 30 and 60 cm, with one sampler at each depth per plot. For each sampler, an 8-cm-diameter hole was bored to the appropriate depth and the sampler inserted. Sand was used to fill any space between the sampler and soil. Soil was then used to backfill the hole, taking care that the tygon tubes were not constricted. To hold the tubes above the soil surface, both tubes from a sampler were inserted through a 5-cm-diameter PVC pipe that was buried approximately 15 cm in the soil. Soil temperature was measured with thermocouples at a depth of 60 cm in each plot that were constructed following the method of Culik et al. (1982). Measurements were made at the end of a ponding event at the time water samples were collected.

Before any experimental flooding occurred, pits were dug in each plot to describe the soil profile and collect soil samples that represented the original soil conditions. Estimates of percentages of specific redoximorphic features were made using reference charts for comparison. Soil samples were collected in 15-cm increments to a depth of approximately 1 m. Before the pits were filled in, the pit walls were lined with a geotextile to mark the wall positions for future reference (Darmody and Bicki 1989). Pits dug in 1993 and 1994 were placed in the same spot as the ones dug in 1992.

The original experimental plan called for the wetland to be flooded twice during the growing season for three years, with each flood lasting approximately 10 d. The channel in the experimental site had stop-log dams at each end (Figure 2). To begin a flood, the dam at the downstream end was closed while the dam at the upstream end was opened. Water was allowed to enter the channel and spill onto the flood plain until all soil plots were inundated with approximately 15 to 20 cm of water. The upstream dam was then closed, and the water was allowed to sit on the soils for a period between 7 to 14 d. At the end of the flood, the dams at the downstream end were opened to allow the site to drain. Dams at the downstream end were left open until the next flood was allowed to occur. The flood water was pumped from the Des Plaines River through a pipeline that emptied into a series of slow-flow channels that brought the water to the entrance of the channel used in the experiment.

Water samples were collected along with measurements of water potential and water-table depth in all plots in May and August of 1992, 1993, and 1994. Samples were collected only at the end of an inundation period. While the surface was covered with water, soil-water samples were collected in a vacuum chamber constructed from a 1-L graduated cylinder. The plastic cylinder was cut in half, and a two-hole rubber stopper placed in the opening. Tubing connectors were placed in each hole of the stopper, and tygon tubes were fitted to each. One tygon tube was attached to the hand-operated vacuum pump (cat. no. 01-071A, Fisher Scientific Co., Pittsburgh, PA 15219-4785), while the end of the other tube was fitted with a quick-disconnect tubing connector that allowed it to be attached to the water sampler tube that led to the bottom of the buried sampler bottle. To collect a sample, vacuum was applied to the chamber until approximately 50 ml of water had accumulated. The vacuum was then released from the chamber, the stopper removed, and the sample was poured into a 50-ml plastic bottle that was quickly capped. Between sample collections, the vacuum chamber was rinsed with distilled water.

Following the first ponding event in 1992, core samples were collected in each plot using a 2.5-cm-diam. hand probe to examine redoximorphic features in detail to a depth of 30 cm. In May of each of the following years, samples were also collected following a ponding event with a coring device to a depth of 1 m in 15-cm increments. In August, soil pits were dug with a small backhoe to describe soil profiles and collects samples at the end of a flood. Profile descriptions were completed for all cores, and hydric soil field indicators were identified. The profiles were then separated into 15-cm depth increments, and bulk soil samples were collected and bagged.

Soil samples from each plot were oven-dried and ground to pass a 2-mm-mesh sieve. Total C was determined by loss on ignition using a high temperature (1500 °C) induction furnace (Nelson and Sommers 1982). Soil pH was determined electrometrically in a 1:1 soil to water mixture. Available P was determined as soluble P extracted with a 0.5 M solution of $NaHCO_3$ (Olsen and Sommers 1982). Exchangeable Ca, Mg, K, and Na were determined by the ammonium acetate method of Thomas (1982). Cation exchange capacity (CEC) was determined by sum of bases, with exchangeable acidity determined from a measurement of buffered pH. Organic C was computed as the difference between total C and inorganic C. Free iron oxides were determined by the methods of Olson and Ellis (1982).

Ferrous Fe (Fe^{2+}) and pH for all water samples were determined within 3 hr of collection at the on-site laboratory to keep the oxidation of Fe to negligible levels. Ferrous iron was determined spectrometrically by taking a 25-ml subsample from each bottle, adding 1 g of 1,10 phenanthroline powder to it, and shaking. Twenty-five ml of the remaining sample were used to standardize the Hach DR/2000 spectrophotometer (Hach Co., POB 389, Loveland, CO 80539). The amount of Fe^{2+} was then determined directly by the spectrophotometer and the sample discarded. The sample pH was determined electrometrically on the water sample not containing 1, 10 phenanthroline. Following the pH measurement, the samples were shipped to North Carolina State University (NCSU) for determination of total dissolved organic C by the procedure of US EPA (1979).

RESULTS AND DISCUSSION

Surface inundation of a site with stagnant water is termed ponding, while inundation with moving water is called flooding (Soil Survey Staff 1993). The experiments were designed to produce ponding events

Table 1. Ponding history for the flood plain wetland. Controlled ponding events were begun and stopped by the authors. Natural events were beyond experimental control. Water depths for controlled events were 15 to 20 cm, while in natural events water depths may have exceeded 1 m.

Ponding Event	Ponding Dates Beginning	End	Ponding Duration Days	Type of Event
		1992		
1	July 27	August 3	7	controlled
2	August 28	September 8	11	controlled
		1993		
3	March 25	March 29	4	natural
4	April 1	May 13	43	natural beginning
5				controlled end
6	June 19	June 29	10	natural
7	June 30	July 19	19	natural
	July 29	August 9	11	controlled
		1994		
8	May 12	May 26	14	controlled
9	June 25	July 8	13	controlled

lasting up to 14 d. To meet wetland hydrology requirements the soils had to be saturated for approximately 10 d, which was 5% of the growing season for this area. The soils experienced nine separate ponding events during the 3-yr study period (Table 1). Durations of inundation ranged from 4 to 43 d. Duration of the controlled ponding events ranged from 7 to 14 d. The target duration was not met in all cases because occasional procedural problems developed with the dams that produced a range of ponding durations. In addition, natural floods also inundated the site during 1993 with durations that ranged from 4 to 43 d. These floods coincided with extensive regional flooding that occurred throughout the midwestern United States that year. Depths of water over the experimental plots during natural floods were not measured, but eyewitness accounts led us to believe that water depths could have been 1 m or more.

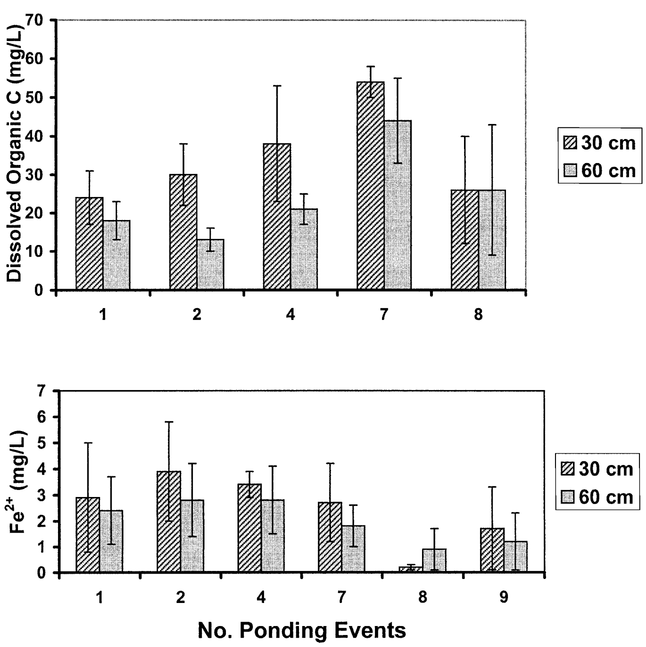

Figure 3. Changes in concentration of dissolved organic C (DOC) and ferrous Fe (Fe^{2+}) measured at the end of each ponding event. The organic C data suggest that adequate organic material was present to support development of anaerobic conditions. The Fe data indicate that Fe reduction was occurring to a depth of 60 cm. Data are means of samples collected from all plots. No samples were collected during natural floods, and only dissolved Fe was measured in samples for the ninth ponding event.

The water dynamics in this experiment differed from those of our earlier study (Vepraskas et al. 1999), which was conducted on the edge of an upland. The soils on flood plains like this one receive oxygenated water from the stream, and the water inundates the previously unsaturated soils. Water quickly recharges the soil by saturated and unsaturated flow. Piezometer data (not shown) indicated that, during a ponding event, the soils were saturated to a depth of 100 cm. At the cessation of a ponding event, the positions that remained inundated the longest were at the mid-plain and at the flood plain's edge.

Soil temperatures ranged from 13 to 18 °C during the time the soils were under a controlled ponding event over the 3-yr study period. Anaerobic conditions developed during all experimental ponding events and were confirmed by measurements of dissolved Fe^{2+} in the ground water (Figure 3). Mean values for Fe^{2+} were consistently $<$4 mg/L. While low, these values

Table 2. Soil chemical data for two horizons of a representative soil of the flood plain wetland. Data are means obtained for the two plots in the mid-plain position, in June 1992 and August 1993.

Chemical Property	A horizon	C horizon
Depth (cm)	0 to 15	45 to 65
pH	7.8	8.1
Organic Matter (%)	4.2	1.1
Available P (kg/ha)	20	5
Exchangeable K (kg/ha)	123	101
Exchangeable Mg (kg/ha)	1859	1612
Exchangeable Ca (kg/ha)	7704	5881
Exchangeable Na (kg/ha)	93	78
Cation exchange capacity (cmol/kg)	25	19

are sufficient to form Fe deposits around roots (Mendelssohn et al. 1995) and were similar to values found in the created deep marsh that was studied by Vepraskas et al. (1999). Soil water pH ranged between 6.78 and 7.31 over the 3-yr period at depths of 30 and 60 cm. Soil pH was higher than this (Table 2), but a reduction of the soil water pH as recorded here is typically found in submerged alkaline soils due to an increase of CO_2 in the solution (Ponnamperuma 1972).

Dissolved organic C concentrations (DOC) also increased during ponding (Figure 3). The DOC values were consistently >10 mg/L, which is the minimum value estimated by Daniels and Buol (1992) that is necessary to support Fe reduction in soils. This indicated that the amount of Fe^{2+} in solution was not limited by the availability of an oxidizable C supply but may have been constrained by low amounts of reducible Fe^{3+} in the soils. These data indicate that durations of inundation lasting 7 to 11 d were sufficient to reduce and solubilize Fe oxides, which is the first step toward forming redoximorphic features and some hydric soil field indicators.

Changes over time in the distribution of oxalate extractable Fe in the soils are shown in Figure 4. Oxalate extractable Fe is poorly crystalline and the first form of Fe oxide to be reduced following the onset of anaerobic conditions (Schwertmann and Taylor 1989). Prior to any ponding, oxalate Fe contents were greatest near the surface. After nine ponding events, the mean oxalate Fe contents in the upper 45 cm of the soils were about one-half of the values prior to ponding. The Fe reduction was removing Fe from this zone. Some of the reduced Fe may have been accumulating deeper in the profile, but our sampling methods were not sufficient to prove this.

During the study, progressive changes were noted in the colors of the A horizons, which showed that the Fe was being reduced in microsites. The constructed

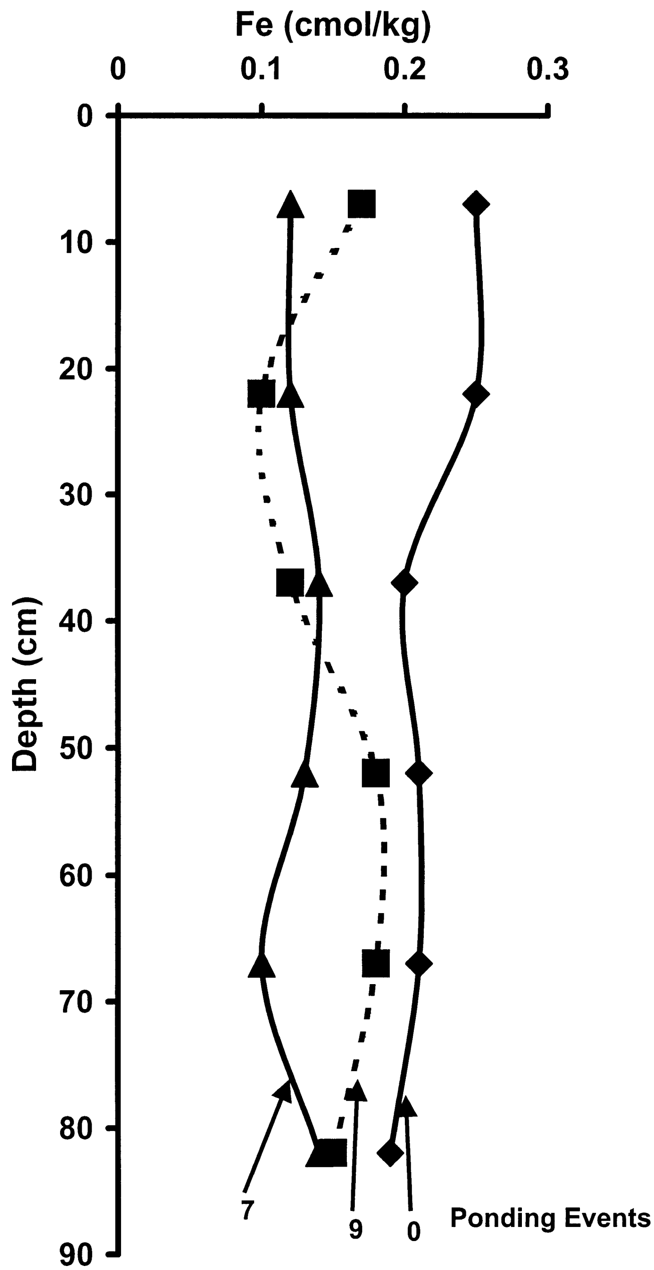

Figure 4. Mean values for oxalate-extractable Fe oxide distribution with depth and over time for all plots. Prior to ponding the Fe concentrations were high in the A horizon (8 to 41 cm thick). The reduction and removal of Fe that occurred during ponding events lowered the Fe levels to about half of what they were originally in the A horizon. Standard deviations were approximately +0.06 cmol/kg for all depths and ponding events.

soils on the flood plain consisted of A horizons overlying C horizons and the soil chemical properties of both are summarized in Table 2. Profile descriptions for the plots to which topsoil had been applied are given in Table 3 for two time periods: before any floods had commenced and after nine events. Prior to

Table 3. Soil morphology of plots in one replicate plot at the mid-plain position on two dates: before any inundation and after nine ponding events. Results are representative of what was observed in the other plots. Observations made prior to ponding were completed within two months following flood plain construction.

Horizon	Depth cm	Matrix Color	Redox Concentrations	Redox Depletions	Textural Class	Comments
			Prior to Ponding			
A	0 to 43	2.5Y 2.5/1	None	None	Silty clay loam	Formed by replacing topsoil over C horizon material
AC	43 to 53	10YR 6/4 (85%)	7.5YR 5/8 (15%)	None	Silty clay loam	
2C	53 to 102+	7.5YR 6/2 (35%)	7.5YR 5/8 (20%)	7.5YR 6/2 (35%), 5GY 7/1 (10%)	Silt loam	
			After Nine Ponding Events			
A1	0 to 18	2.5Y 2.5/1	10YR 6/4 (10%), 7.5YR 5/6 (7%)	2.5Y 4/3 (10%)	Silty clay loam	
A2	18 to 36	2.5Y 2.5/1	10YR 6/4 (10%) masses, 10YR 5/8 (1%) pore linings	5Y 4/2 (5%)	Silty clay loam	Redox concentrations are Fe pore linings assoc. with the depletions
2Cgl	36 to 56	2.5Y 6/2	10YR 5/6 (15%), 7.5YR 5/8 (10%)	5BG 6/1 (5%)	Silt loam	
2Cg2	56 to 79+	2.5Y 6/2	10YR 5/6 (15%), 7.5YR 5/8 (10%)	5BG 6/1 (30%)	Silt loam	

inundation, the A horizon was uniform in color and contained no apparent redoximorphic features. After nine ponding events, two A horizons had developed that differed in the percentage of redox depletions and redox concentrations observed. The C horizons contained redoximorphic features both before and after the nine flood events. Small changes were noted in C horizon matrix hue and in the hues of redox depletions and concentrations (Table 3).

The characteristics of the redox depletions observed are shown in Table 4 for two plots. Depletions were spherical bodies that were generally 10 to 20 mm in diameter. Hues were 2.5Y or 5Y with some gleyed hues found occasionally; values were 4 or 5 and chromas were 3 or less. In most cases, the depletions contained small (<1 mm diam.) redox concentrations (Fe masses or pore linings) within the depletion or around its perimeter. Changes in depletion abundance with ponding events are shown in Figure 5. Mean values for depletion abundance, as well as the range in abundance, tended to increase up to the ninth ponding event. However, the largest change occurred between the first and fourth ponding event that included the natural flood that lasted 43 d. The individual effect of this large flood on depletion abundance is not known.

The boundary between the depletions and topsoil matrix was sharp rather than diffuse. Depletions generally occurred in the bottom half of the topsoil cover

Table 4. Properties of the redox depletions (iron depletions) formed in the A horizons at two positions in the flood plain wetland in plots that had topsoil placed on the surface. Original matrix color was black (5Y 2.5/1 moist). No depletions were observed in the A horizons prior to inundation.

Floodplain Position	Feature Characteristics	Number of Ponding Events (Year)		
		1 (1992)	6 (1993)	9 (1994)
Edge	Abundance (%)	2	5	25
	Color†	2.5Y 4/1, 5/2	5Y 4/1, 4/2 5GY 4/1, 5/1	2.5Y 4/2
	Size (cm)	0.2 to 1	0.1 to 4 cm	0.1 to 2
Mid-Plain	Abundance (%)	3	10	15
	Color	2.5Y 4/2, 5/2	5Y 4/1, 4/2 5GY 4/1	2.5Y 4/1, 4/2
	Size (cm)	0.1 to 2	0.1 to 2	0.1 to 4

† Colors are moist colors for the depletions only. Most depletions contained Fe pore linings and masses that were <1 mm in size and had a color of 7.5YR 5/8 or 2.5Y 5/4 (moist).

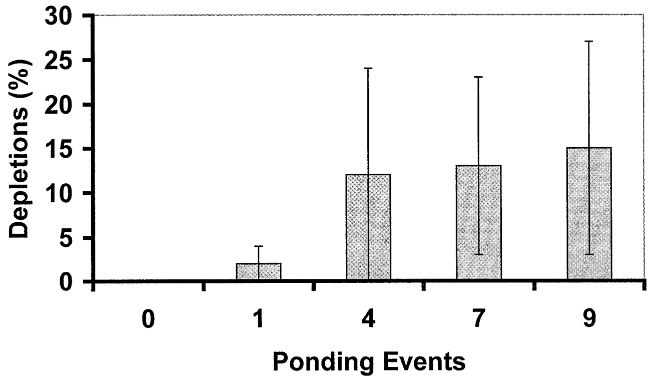

Figure 5. Changes in the percentages of redox depletions in the A horizons of all plots with ponding events. Data are means and standard deviations. The first ponding event produced approximately 2% depletions, which are too few to form a hydric soil field indicator. Although the variability was high, the percentages of Fe depletion remained relatively constant after the fourth ponding event.

in a random distribution. Most depletions had a zone of Fe concentration either within the depletion or along its perimeter. The iron concentration was frequently an iron pore lining that formed along a crack or root channel in the center of the depletion. Thus, formation of the Fe pore linings appeared to be related to the formation of the depletions.

The depletions contained redox concentrations at their center, which were usually Fe pore linings but occasionally were also Fe masses. Colors of these redox concentrations were generally 7.5YR 5/8 or 10YR 5/8. The Fe pore linings were accumulations of Fe that formed around small root channels (1 mm diam.) or small cracks. These are similar to the oxidized root channels reviewed by Mendelssohn et al. (1995) but differ in that the O_2 enters the soil following drainage rather than being exuded by roots. Features described as Fe masses were similar to the pore linings except that no channel or crack was visible within them. These redox concentrations occupied $<2\%$ of the horizons. The occurrence of Fe pore linings within the depletion suggested that both features formed at the same time by oxidation-reduction processes.

Analysis of selected depletions collected after nine ponding events showed that they contained 2.6 g/kg of oxalate extractable Fe compared with 3.2 g/kg in the matrix. These are the mean values for two samples composited from the individual depletions that were analyzed. These differences are small, considering the relatively large difference in color, but this is partly a result of our inability to separate the grayish depletion from small concentrations of Fe that were sometimes contained within the depletions. Organic C levels were also slightly lower in the depletions (0.2 g C/kg) than in the matrix (0.4 g C/kg), and this difference also contributed to the color difference between depletions and matrix. These chemical changes clearly affected the appearance of the depletions. Their grayish base color was revealed through loss of C, which removed the dark color of the matrix, while the gray color itself was produced when Fe oxides were reduced and removed from the surfaces of mineral particles.

The grayish colored depletions are probably formed by intense microbial activity occurring in a microsite (0.1 to 4 cm diam.) that will eventually become an iron depletion (Figure 6). Such microbially-active microsites have been described previously in research on denitrification (Parkin 1987) and methane production (Crozier et al. 1995). Parkin (1987) described how, in his experiments, denitrification ''hot-spots'' occurred around particulate organic material such as a decaying leaf. In the microsites observed here, we did not identify the organic components responsible for the microsite formation. To form a depletion, we hypothesize that the organic matter is oxidized and Fe^{3+} oxides are reduced to Fe^{2+} ions. The soluble Fe^{2+} ions diffuse through the zone of reduction and precipitate (following oxidation) along root channels or cracks that contain oxygen. The oxygen may diffuse into the soil following cessation of the flood and drainage of the soil. Formation of Fe depletions should continue as long as both Fe oxides and organic matter occur in the topsoil cover.

The loss of C from the depletions apparently is related to the microbially induced Fe reduction. It has been shown that Fe oxides of various types bind soluble organic materials to their surfaces (Jardine et al. 1989, Kretschmar et al. 1993, Kaiser and Zech 1998). It is possible that organic C was released from soil particles when the Fe oxides were reduced and dissolved. This would also increase DOC, as we detected. Some of the organic C lost from the depletion may also have been oxidized by the microbes.

The Fe depletions and Fe pore linings found in the topsoil cover of the flood plain wetland have been observed in the deep marsh at the Des Plaines site and in some natural marsh soils and sedge meadows near the site. We believe that our experiments effectively simulated processes that occur in natural wetland systems. Formation of these redoximorphic features in this short-term study supports their use as indicators of wetland processes and their use as tools for delineating wetland boundaries, even in wetlands inundated for periods as short as seven days. However, as shown in Table 4, the abundance of redoximorphic features increases with the number of ponding events. In addition, long duration ponding events would be expected to produce more depletions than events of short duration, at least up to a point. Soils that have experienced few or short-duration ponding events will have

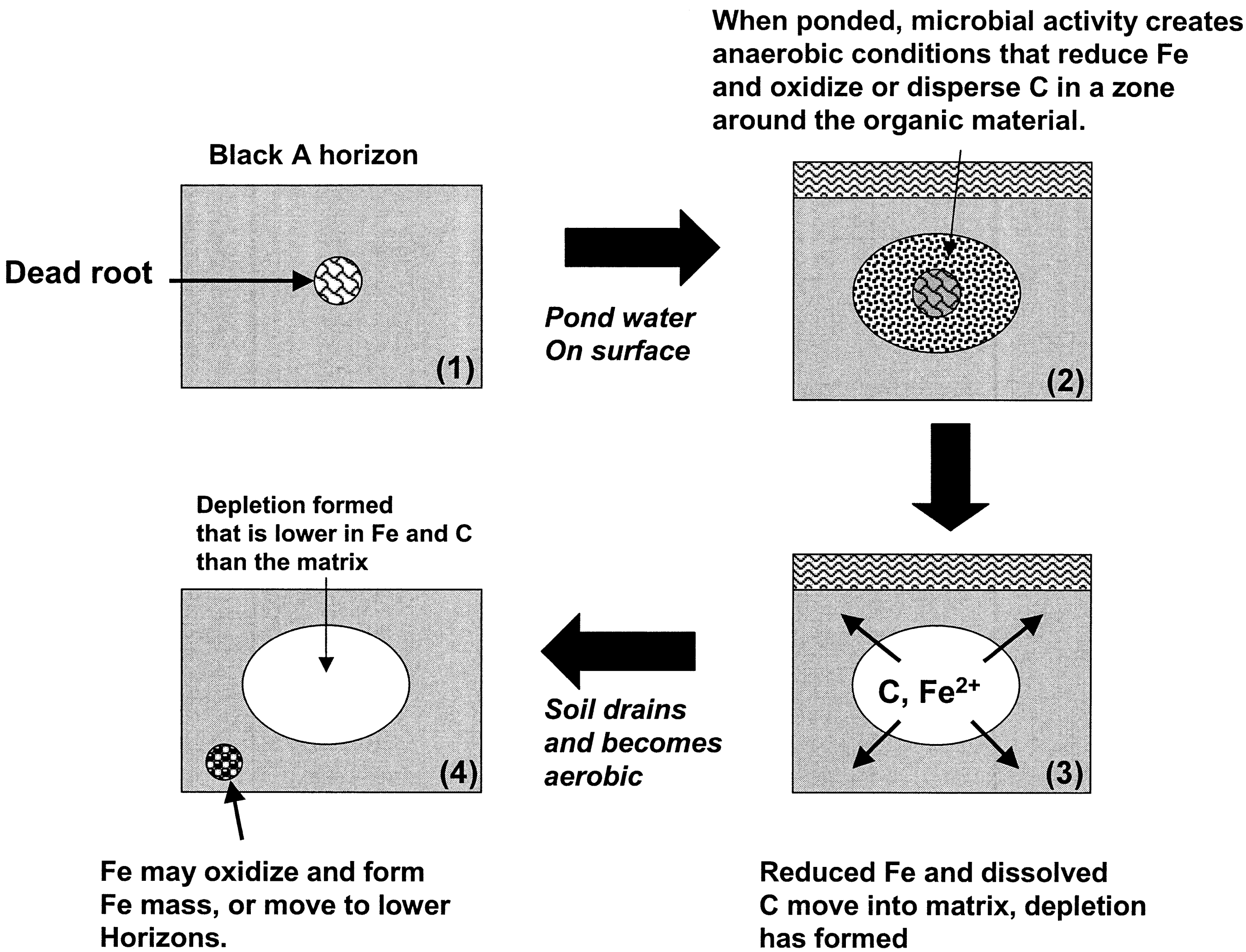

Figure 6. Proposed mode of formation of redox depletions. The process begins (1) when dead root tissue fosters growth of bacteria around it as the tissue is decomposed. When ponded (2), anaerobic conditions develop around the tissue as the bacteria deplete the soil water of oxygen. Iron is reduced in this zone as the growing bacterial colony uses Fe as an electron acceptor. The reduced Fe is in solution and diffuses from an area around the root tissue (3). Organic C is either oxidized or dispersed and also moves out of the reduced zone. At this point, the depletion has formed. When the soil drains and becomes aerobic (4), the reduced Fe may reoxidize and form and Fe mass if it has not moved to lower horizons.

few depletions present, and the quantities may be too small to be seen except by very close observation. The 7-d ponding event only resulted in depletions occupying 2% of the horizon, which is not enough to form a hydric soil field indicator. While the 43-d ponding event contributed to the large increase in depletion abundance between the first and fourth ponding events (Figure 5), the full impact of this event on soil morphology is not known. This natural flood occurred in the Spring when temperatures were cool, and the amount of Fe^{2+} in solution was slightly less than that found for the second ponding event (Figure 3).

The hydric soil field indicators listed in Table 5 were observed at this site over the time period of the study. When and where they appeared in the flood plain are shown in Table 6. Prior to any ponding, most plots met indicator F3 (depleted matrix) because the C horizon, from which the wetland was constructed, met the requirements for the indicator. This indicator did not form during the course of our experiments. Plots in the mid-plain position did not meet the F3 indicator because their A horizons were thick (>25 cm), and this placed the C horizon out of the depth range required for the indicator. Plots in the back-plain position failed to meet indicator F3 after the ninth ponding event because approximately 15 to 20 cm of sediments was deposited on top of the mineral surface. The indicators shown for this position after the ninth ponding event occurred both within the new sediment as well as below it. The sediment was eroded onto the back-plain position from an upslope location.

By the ninth ponding event in the third year of the

Table 5. Definitions of the hydric soil field indicators found at the site (USDA-NRCS 2002). In this study, a variant of field indicator F7 was identified because the depletions formed had a Munsell value of 4 rather than 5.

Symbol	Name	Definition
F3	Depleted Matrix	A layer with a depleted matrix that has 60 percent or more chroma 2 or less [and value of 4 or more] that has a minimum thickness of 15 cm and starts within 25 cm of the surface. The minimum thickness is 5 cm if the depleted matrix is within 15 cm of the soil surface. Redox concentrations are required for certain matrix colors.
F6	Redox Dark Surface	A layer at least 10 cm thick entirely within the upper 30 cm of the mineral soil that has: a matrix value 3 or less and chroma 1 or less and 2 percent or more distinct or prominent redox concentrations as soft masses or ore linings, or b) matrix value 3 or less and chroma 2 or less and 5 percent or more distinct or prominent redox concentrations as soft masses or pore linings.
F7	Depleted Dark Surface	Redox depletions, with value 5 or more and chroma 2 or less, in a layer at least 10 cm thick entirely within the upper 30 cm of the mineral soil that has: a) matrix value 3 or less and chroma 1 or less and 10 percent or more redox depletions, or b) matrix value 3 or less and chroma 2 or less and 20 percent or more redox depletions.

study, all plots had developed at least one field indicator (Table 6). The two most common field indicators formed were F6 and a variant of F7. In this study, the redox depletions found in indicator F7 had Munsell values of 4 and chromas of 2 or less. Indicator F7 requires values to be 5 or more (Table 5). As a result of the low value, we describe the indicator observed in this study as a variant of indicator F7. Indicator variant F7 developed from the redox depletions that may have formed as shown in Figure 6 through Fe reduction and C movement. Indicator F6 formed by the oxidation of reduced Fe around root channels. Formation of the F6 indicator may have accounted for the increase in oxalate Fe shown at the 0–15 cm depth in Figure 4.

These results show that the field indicators are dynamic and can form in relatively short periods of 3 yrs or less when the hydrologic regime promotes Fe reduction. Redoximorphic features such as redox depletions can form after a single ponding event but are not in sufficient quantity to meet a hydric soil field indicator. Our experiments were conducted under controlled conditions where ponding events were made to occur a minimum of twice per year. Natural flood plains where inundation is less frequent, or where organic matter levels are low (i.e., 1%), may require longer periods to form field indicators than the 3-yr period found here.

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Table 6. Summary of changes observed in Hydric Soil Field Indicators for increasing ponding events. Indicators were identified for the four positions across the flood plain for both transects 1 and 2.

No. of Ponding Events	Channel		Edge		Mid-Plain		Back Plain	
	1	2	1	2	1	2	1	2
0	F3	F3	F3	F3	NIM	NIM	F3	F3
4	F3	F3	F3, F7†	ND	NIM	ND	F3	ND
7	NIM	ND	F3, F6	F3, F6	F7†	F6, F7†	F3	F3
9	F3, F7†	F3, F7†	F3, F6, F7†	F3, F6, F7†	F6	F6, F7†	F6, F7†	F6

† The F7 indicator was not met exactly because the depletions observed had Munsell values of 4 whereas values of 5 are required. It is considered a variant of the USDA Field Indicator F7.
NIM = no indicator met.
ND = no data recorded.

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